AlGaAs/GaAs Heterostructure Solar Cells Grown by Molecular Beam Epitaxy

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Abstract

The AlGaAs/GaAs heterostructure solar cells were fabricated by molecular beam epitaxy (MBE), which provides ultra-thin molecular layers of the design structure. The typical efficiency of the solar cells fabricated and their characteristics are η = 17%, V_{oc} = 0.73 V, I_{sc} = 33 mA/cm^2, and F.F. = 0.7. Spectral response of the solar cells show a broad spectrum ranging from 500 to 900 nm, corresponding to the window effect of the AlGaAs and the band edge of the GaAs materials.

Keywords: AlGaAs/GaAs Heterostructure, Solar Cell, Molecule Beam Epitaxy (MBE)

1. Introduction

The molecular beam epitaxy (MBE) is a powerful technique for designing electronic devices with specific structures at a molecular level. The MBE technique is controllable at atomic layers, providing different combinations of the growth materials and ultra-thin structures in nanometer scale. Doping concentration is also uniform due to the lower temperature growth process, compared to the diffusion process in silicon planar technology or the liquid phase epitaxy (LPE) technique. Thus, MBE is an ideal technique for abrupt junction formation of the heterostructure devices, such as light-emitting diodes (LEDs), laser diodes (LDs), photodiodes (PDs) and solar cells, using III-V compound semiconductors [1-4].

The AlGaAs/GaAs heterostructure is a suitable structure for several optoelectronic devices as GaAs is a direct band gap material [5-6]. Furthermore, realization of the wide-gap window effect is very important for solar cell applications. It permits us to broaden the spectral region considerably and control it precisely.

It is well known that in photovoltaic applications, AlGaAs/GaAs heterostructure solar cells yield high efficiency, which results from a wide gap optical window of AlGaAs and a high absorbing effect of GaAs due to its direct band gap property at 1.4 eV [5] Such solar cells can be used in high intensity, high temperature and high radiation conditions; and the solar cells produced in this manner are usually used in satellite technology [7]. Because of its large absorption coefficient, the active thickness of this III-V compound semiconductor in the solar cell structure must be carefully designed for optimal energy output from solar radiation. Ultra-thin layers of the structure in nanometers will lead to a better device performance and also material saving, and this is feasible by employing the MBE technique.

Our Semiconductor Device Research Laboratory (SDRL) installed the MBE machine in 1993 for fabrication of quantum devices [8]. Figure 1 shows our MBE machine. The laboratory has conducted the solar cell research since its establishment in 1975 as a pioneer work in the country. With this proper research equipment and expertise, the AlGaAs/GaAs heterostructure solar cells were fabricated using a simple structure, starting from p-type GaAs substrates. The prime AlGaAs/GaAs heterostructure solar cells, without optimization, show a typical efficiency of more than 17% under AM1 illumination at 100 mW/cm^2. This basic structure would be integrated with the quantum structure like quantum dots in the near future. We could expect some quantum features like intermediate-band solar cells or quantum dot solar cells [9-11] which can be use as high-efficiency solar cells at high solar intensity.

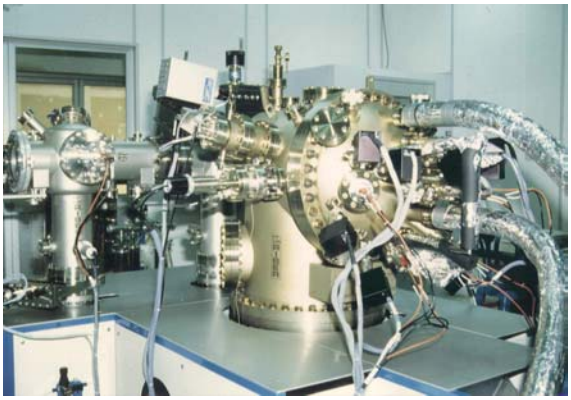

Fig. 1 Molecular Beam Epitaxy Machine at SDRL, Chulalongkorn University.

2. Experimental Procedure

A 5×10^{18} cm^{-3} Zn-doped, p$^+$ (001) GaAs substrate was prepared as the starting material for solid-source MBE growth of different crystalline layers of the heterostructure solar cells. After desorbing oxide at 630 °C under As pressure, the epitaxial growth started with a 1.0-μm-thick GaAs buffer layer, which was grown at 610 °C with a growth rate of 1 monolayer per second (ML/s) in order to enhance the surface morphology and with a Ga beam source at 915 °C. During the growth, the beam equivalent pressure of As_4 was 1×10^{-5} mbar. The in-situ observation is done by employing the reflection high-energy electron diffraction (RHEED), which has been widely used for the study of the MBE growth kinetics and can be used to observe the crystal quality during the MBE growth [3]. RHEED pattern during

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14. ABSTRACT
The contractor shall investigate the integration of quantum dots to the heterostructure of solar cells and the self alignment of quantum dots grown on high-index GaAs substrates for future nano-electronic device applications

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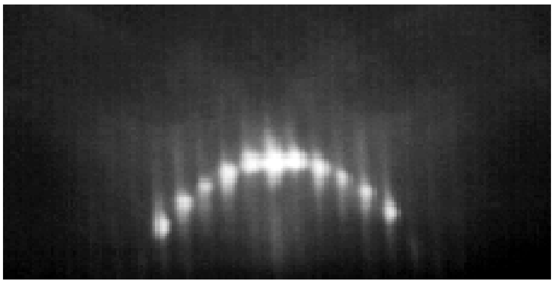

Fig. 2 RHEED pattern of GaAs surface at growth temperature.

growth GaAs is shown in figure 2. Then at the same temperature, a 200-nm n^+-GaAs, using Si as the doping source operated at 1000 °C in the MBE machine with doping concentration 1×10^{18} cm^{-3}, was grown for a PN junction formation. The window layer of n-AlGaAs with 50nm thick and Al content of 0.4 for heterostructure was then grown using Al beam source at 1000 °C. Following the window layer, an ultra-thin capped layer having 20-nm thickness was epitaxially grown to provide stable and non-oxidized surface of the solar cells. After the MBE growth of the whole structure, Au:Ge/Ni was evaporated to form double metallic layers on the front side of the substrate by using a finger-shape pattern metallic mask in the vacuum evaporation machine. The sample was then annealed in N_2 ambient at 475 °C to obtain the ohmic contact. On the other side of sample, AuZn was deposited all over the surface. Similarly, to achieve the ohmic contact, the sample was annealed again in N_2 flowing gas at 375 °C. This fixed finger-shape pattern metallic mask limits the optimal design of the solar cell structure in the present work. Eventually, the sample was cleaved to reduce leakage current along the edges. The surface area of each resulting device is about 5×7 mm^2. The structural diagram of the AlGaAs/GaAs heterostruture solar cell is shown in figure 3.

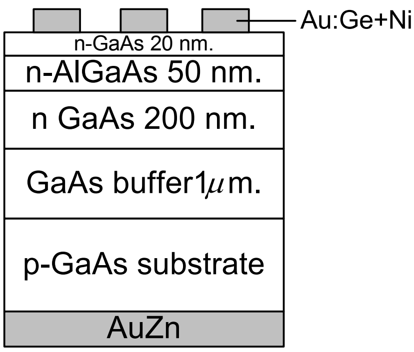

Fig. 3 Structural diagram of AlGaAs/GaAs heterostructure solar cell.

3. Solar Cell Characterization

The solar cell samples grown by the MBE technique were characterized for I-V curves in the dark and under 100-mW/cm^2 AM1 illumination from solar simulator. Figures 4 and 5 are typical I-V curves of the AlGaAs/GaAs heterostructure solar cells in the dark and under illumination, respectively. It is seen that the curve passes through the fourth quadrant. Reverse saturation current of the devices shows large leakage current at the junction. This reflects a low open-circuit voltage and a low fill-factor of the solar cells. The experimental results show that V_{oc} = 0.73 V, J_{sc} = 33 mA/cm^2, and F.F. = 0.7, leading to 17% efficiency in the present work.

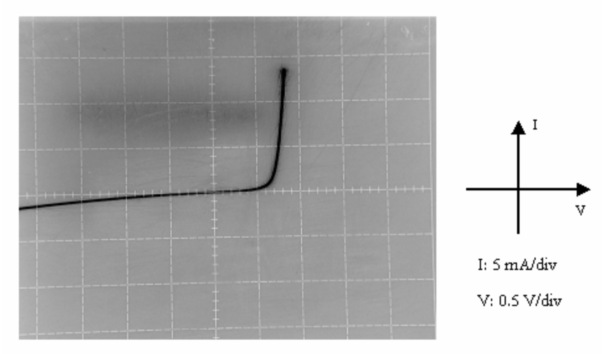

Fig. 4 showing typical I-V curve at dark.

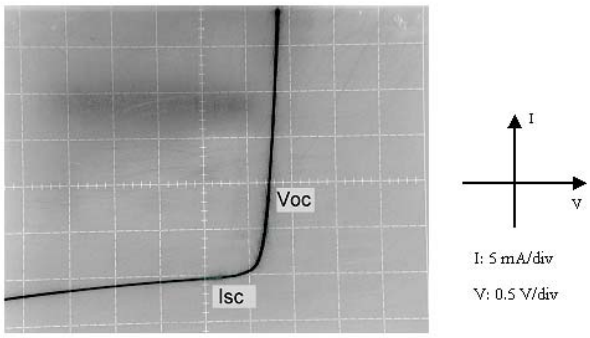

Fig. 5 I-V curve at 100 mW/cm^2 AM1 under solar simulator showing 17% solar cell efficiency.

The result of the spectral response measurement of the AlGaAs/GaAs heterostructure solar cells is shown in figure 6. The broard spectrum of the photo-current ranging from 500 to 900 nm could be explained by the window effect of AlGaAs having a wide band gap at the short wavelength region and by the direct gap of GaAs having proper 1.4 eV band gap at the sharp-drop long wavelength of 900 nm.

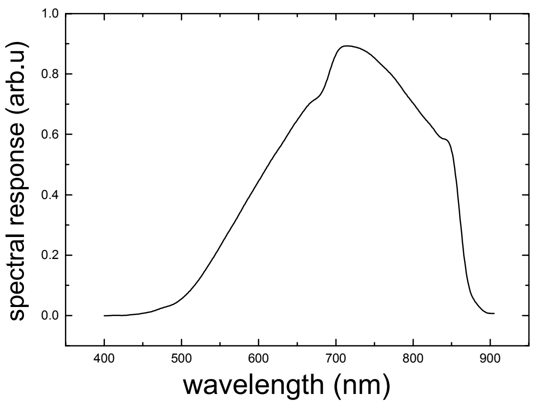

Fig. 6 Spectral response of AlGaAs/GaAs heterostructure solar cells ranging from 500 to 900 nm.

4. Discussion

The principle of the solar cell is based on large-area junction with a shallow junction having high uniformity. The MBE technique could provide all requirements, i.e., large area and ultra-thin crystal layer with high uniformity and high-quality crystals, and with uniform doping profile necessary for abrupt junction. Since the solar spectrum is broad by nature, the window effect for high-performance solar cells is also feasible by MBE using lattice-matched AlGaAs mixed crystals. Therefore, the solar cell structure made from III-V compound semiconductors could be optimized and freely fabricated by MBE, inspite of the high-cost equipment investment. Nevertheless, a novel solar cell structure integrated with nano-quantum features like quantum wells or quantum dots could be realized by this growth method.

In this present experimental work, Be doping for p-GaAs is avoided for technical reason. We, therefore, choose to start with the p-GaAs substrate and grow only the n-type GaAs and AlGaAs using silicon doping source for PN junction formation. Also, V_{oc} can be different for n^+ and p^+-substrate cells with the same material because of non-uniform generation in the base region or in the absorption region, and unequal diffusion coefficients of electrons and holes; the electron-diffusion length is usually larger than the hole diffusion length. Therefore, an extra voltage, called the Damber potential, appears in the base region, which assists carrier collection for a p-type base, but resists carrier collection for a n-type base region [6]. However, an ideal junction should be created without any thick intrinsic layer in between and with defect-free crystalline quality. Further improvement of the structure could be done by thickness optimization and Be-doping for solar cells using n-GaAs substrates.

GaAs-based solar cells should give $V_{oc} \cong 1$ V for an ideal case, but our experimental result gives V_{oc} = 0.73 V only and also large reverse saturation current in the dark. This implies that leakage current from the junction is the main origin of poor solar cell performance, leading also to a low fill factor. However, I_{sc} = 33 mA/cm^2 at 1 sun is quite hopeful for high-power source at strong intensity (100~1000 suns) operation.

5. Conclusion

AlGaAs/GaAs heterostructure solar cells fabricated by molecular beam epitaxy technique were demonstrated. Reasonable performance with η = 17% was obtained. Further improvement by reducing reverse saturation current would be a key direction. This fabrication technique could be modified for future solar cell with nanostructure having some novel performances like two-photon process through intermediate band and broader spectral response.

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